RESEARCH DEPARTMENT

# Line-store standards conversion: the subjective determination of the necessary number of stores

RESEARCH REPORT No.T-123

1964/13

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

# LINE-STORE STANDARDS CONVERSION
# THE SUBJECTIVE DETERMINATION OF THE NECESSARY NUMBER OF STORES

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A.H. Jones, B.Sc., Grad. I.E.E.

D. Maurice

(D. Maurice)

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## SUMMARY

This report gives an outline of measurements made in order to assist in determining the number of stores required in a line-store standards converter.[1] A series of subjective tests was carried out in order to assess the effect of sampling a television picture at a constant rate, the sampling being coherent from one line to the next. It was found that the picture may be reconstructed from the samples without noticeable impairment, provided the rate of sampling is not less than a minimum that is dependent on the characteristics of the filters which limit the video spectrum before and after sampling. Various types of interlaced sampling were tried; however, none would permit the use of a sampling frequency significantly lower than that determined by the filter characteristics without noticeable impairment of the reproduced picture.


## 1. INTRODUCTION

An essential process of standards conversion is the redistribution of video information in time. In a line-store converter[1] this is carried out by writing each incoming picture element into one of a series of identical stores; this process continues at equal intervals throughout an input line period. The information held by each of the stores is then 'read out' in a uniform sequence throughout an output line period. The effect of this is to sample[2] the picture signal at a uniform rate, the sampling being coherent from one line to the next. The number of stores required in a line-store converter is therefore equal to the number of samples that need to be taken during an input line period in order to produce an acceptable output picture; no allowance need be made for the line-blanking period since this may be synthetically reconstructed.

A well known sampling theorem* states that, if a function $f(t)$ contains no components at a frequency higher than $w$ c/s it is completely determined by specifying its magnitude at a series of points spaced $1/2w$ seconds apart. This theorem

* This theorem has been advanced by Shannon,[3] Gabor,[4] and Nyquist,[5] though it was derived from previous work by Whittaker,[6] and was known to Cauchy.[7,8] It will be referred to in this report as 'the sampling theorem'.

implies that, if all the information contained in a video signal is to be carried by a train of amplitude modulated samples, the sampling rate must be not less than once per picture element.

It was not, however, known whether the sampling theorem could be applied directly in order to derive the minimum sampling rate, and hence the number of stores required for a practicable line-store standards converter. In such a converter sampling is coherent from line to line and filters having a limited rate of cut-off are used to limit the input and output video spectra. A subjective appraisal was made, therefore, of the picture quality resulting, under these conditions, from sampling at various frequencies. This gave data from which the minimum number of stores necessary to produce an acceptable output picture from a line-store converter was deduced.

It has been suggested[2] that some form of interlaced sampling may permit the use of a lower sampling frequency than that prescribed by the sampling theorem. Simple interlacing of samples is effected by periodically delaying the sampling pulses by half the sampling period. Three simple methods of interlacing were investigated in order to determine whether they would enable an acceptable picture to be produced using a reduced number of stores. In the first method, the delay producing interlaced samples was inserted during alternate line periods, in the second method the delay was inserted during alternate field periods and, in the last method, the delay was inserted during two successive lines of a five-line sequence.

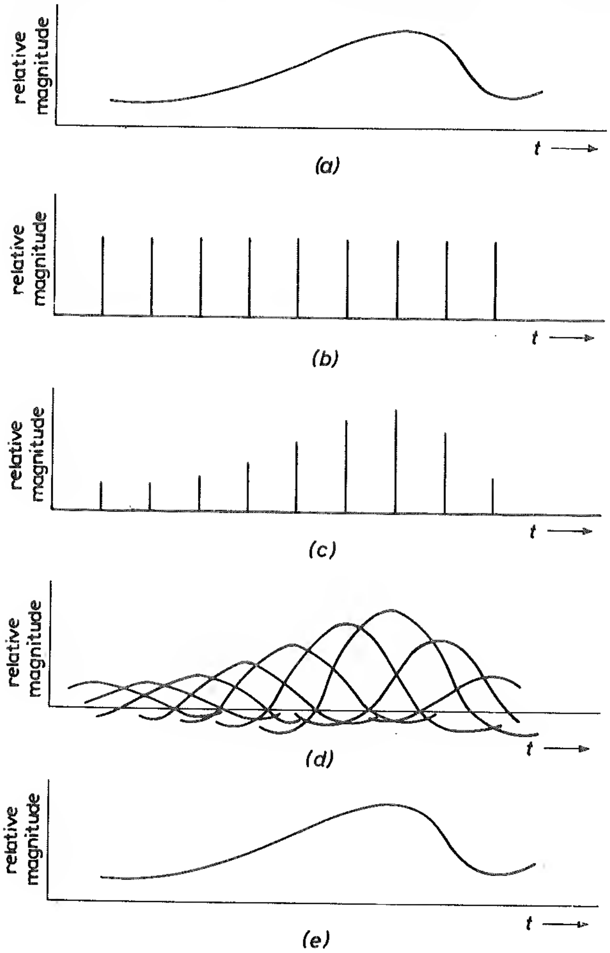


*Fig. 1 - Effect of sampling on signal waveform*

(a) Video input signal
(b) Sampling pulses
(c) Sampled video signal
(d) Filtered samples
(e) Video output signal

## 2. GENERAL

### 2.1. Sampling

The effect of sampling a video waveform with narrow repetitive pulses is shown in Figs. 1 and 2, Fig. 1 showing the time functions and Fig. 2 the corresponding frequency spectra. The video signal, occupying a band from d.c. to $f_v$, amplitude modulates the sampling pulses, so that the video-frequency components form sidebands clustered around the sampling frequency $f_s$ and its harmonics (Fig. 2(c)). The original video spectrum is present as a zero-order sideband; this component may be recovered unchanged from the sampled signal by means of a

low-pass filter, provided that $f_s$ is sufficiently high (Figs. 1(d), 1(e) and 2(d)). When $f_s$ is lowered, the sideband clusters are brought closer together until they overlap. The sidebands around $f_s$ then intrude into the video band, producing additional 'image' components. An overlap occurs when $f_s$ is less than twice the highest video frequency $f_v$; this accords with the sampling theorem.

However, the low-pass filters used in practice to define the video spectrum at the input to the sampler and to remove unwanted components at the output have imperfect characteristics. The spectrum of the signal applied to the sampler is, therefore, of the form shown in curve (a) of Fig. 3, and the sampler output is of the form shown in curve (c) of Fig. 3. Curve (c) indicates that, in order to

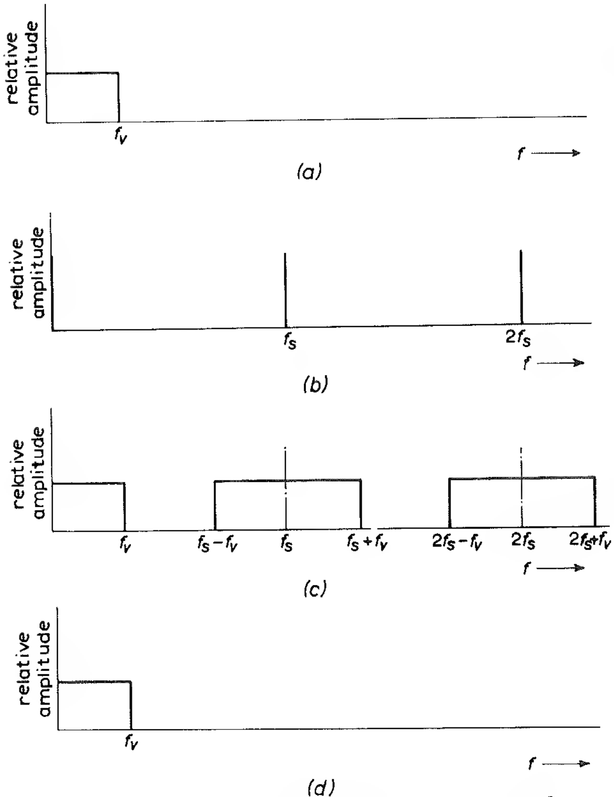


*Fig. 2 - Effect of sampling on signal spectrum*

(a) Spectrum of video input signal
(b) Spectrum of sampling pulses
(c) Spectrum of sampled video signal
(d) Spectrum of video output signal

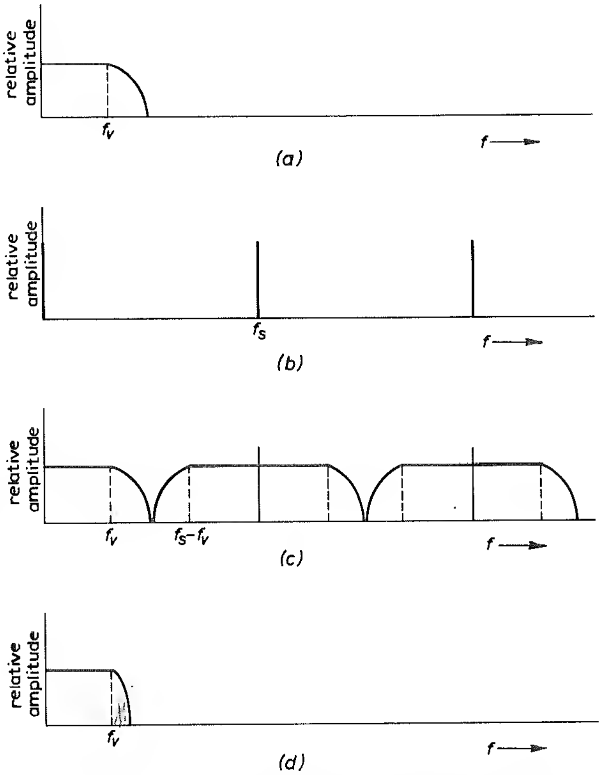


*Fig. 3 - Signal spectrum when sampling with imperfect filters*

(a) Spectrum of video input signal
(b) Spectrum of sampling pulses
(c) Spectrum of sampled video signal
(d) Spectrum of video output signal

exclude image components from the filtered output, $f_s$ must be greater than 2 $f_v$ by an amount that depends on the characteristics of the filters. If the rate of cut-off of the filters were increased, the sampling frequency could be reduced somewhat but the design and construction of the filters would be more complicated. Thus the characteristics of the filters used in a line-store converter are important factors in determining the number of stores required; the use of a more complex filter design may enable the number of stores to be reduced.

When imperfect filters are used, the minimum sampling frequency necessary to produce an acceptable output picture can only be determined by subjective tests,

since it depends also on the visibility of those image components that are allowed to fall within the output video band. The subjective tests described in this report were carried out using filters that were considered to be closely representative of those suitable for use in a line-store converter.

Before experimental work was undertaken an attempt was made to deduce a theoretical minimum sampling frequency $F_s$ using the results of tests carried out on the subjective effects of co-channel interference; the way in which this was carried out is explained in the Appendix. It was concluded that if a line-store converter uses high-grade low-pass filters of a certain type[9] with cut-off frequencies chosen to suit the required input and output signal bandwidths, the writing process should sample the incoming signal at a frequency which is twice that at which the input filter attenuates by 20 dB.

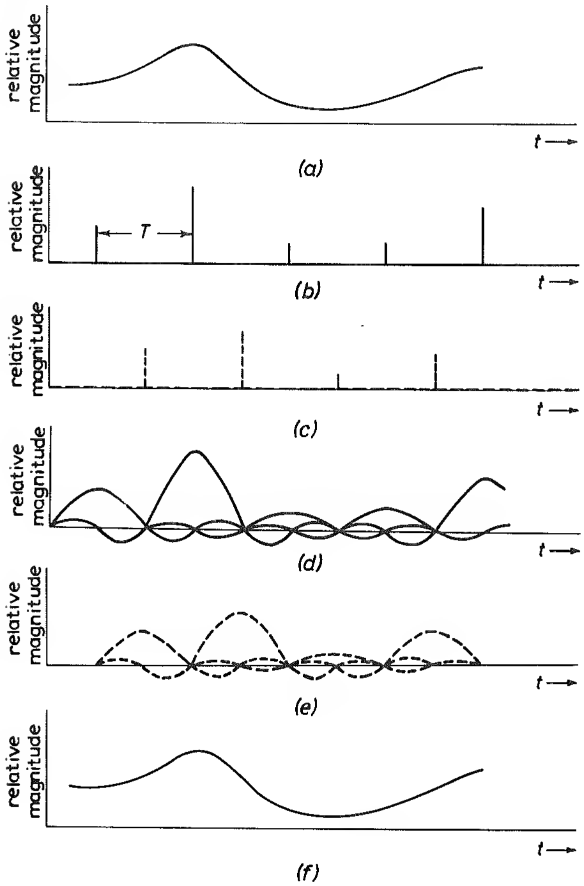


*Fig. 4 - Idealized effects of interlaced sampling*

(a) Video input signal
(b) Samples during odd field periods
(c) Samples during even field periods
(d) Filtered samples during odd field periods cut off frequency = $1/T$
(e) Filtered samples during even field periods cut off frequency = $1/T$
(f) Resultant, if integration is complete

### 2.2. Interlacing of Samples

When interlaced sampling is employed, one set of samples is made to interleave with another. This means that when image components are present in the output, as a result of sampling at an insufficiently high frequency, the spurious patterns that are produced in the displayed picture by one set of samples are in phase opposition to those produced by the other set of samples. There is, therefore, a partial cancellation of their subjective effects by the integrating action of the eye. This is similar to the partial cancellation of interfering effects that results from the frequency-offset operation of television transmitters.[10] Fig. 4 further illustrates the process and shows one arrangement theoretically permitting the sampling frequency to be halved when samples are interlaced.

In practice, however, the integrating action of the eye is not complete, and the interlacing of samples is likely to introduce additional undesirable effects when the sampling frequency is low.

Fig. 5 shows, on a 625-line raster, the sampling positions that result from three simple interlace arrangements. Since the picture contains an odd number of lines, one-to-one line interlace (Fig. 5(a)) produces a sampling pattern that

takes four field periods to repeat, and subjectively introduces crawling serrations at high-contrast vertical edges. A field interlace of one-to-one (Fig. 5(b)) produces a sampling pattern that repeats once every two field periods, and introduces serrations, at vertical edges, which are stationary but flickering at 25 c/s. Since 625 is divisible by five, three-to-two line interlace (Fig. 5(c)) produces an interlace pattern that repeats once every two field periods; although the serrations that it introduces at vertical edges do not flicker or crawl, they are asymmetrical and of coarse structure. The purpose of the interlace tests was to determine the extent to which the sampling frequency could be significantly reduced, below that necessary without interlacing, before these additional defects became objectionable.

## 3. APPARATUS

Fig. 6 is a block schematic diagram of the apparatus used. The video signals were provided by a flying-spot slide scanner operating at the 625-line, 50-field standard. These signals were first passed through the input filter and amplifier and thence to the sampling gate. The output from the sampling gate was then amplified and passed through the output filter.

The sampling gate consisted of four fast-acting diodes connected as shown. In order to increase the signal level obtained from the samples, a

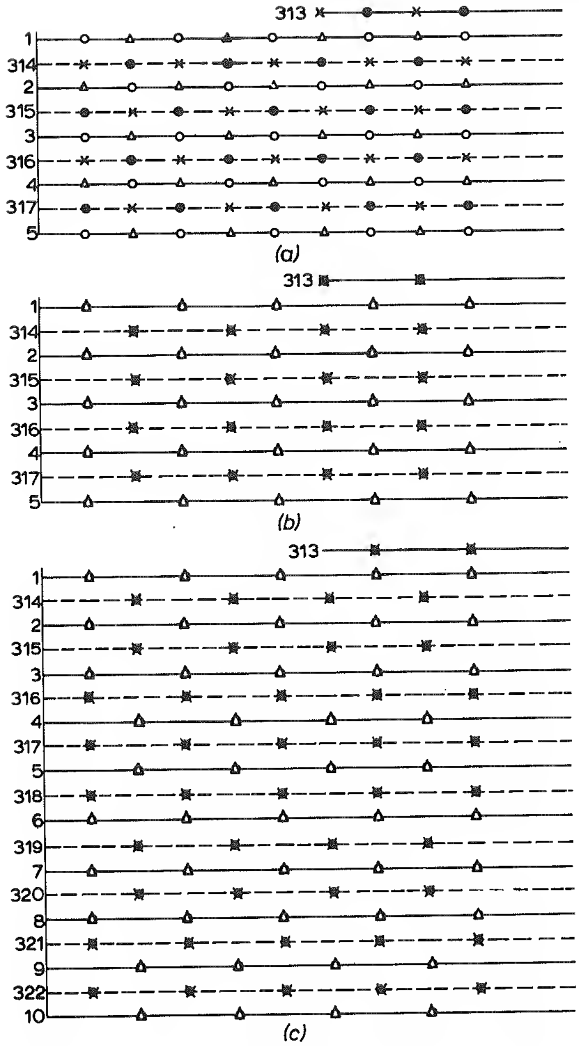


*Fig. 5 - Three simple interlacing arrangements*

(a) 1:1 line interlace
(b) 1:1 field interlace
(c) 3:2 line interlace

○ Sample positions during first field period
● Sample positions during second field period
Δ Sample positions during third field period
× Sample positions during fourth field period

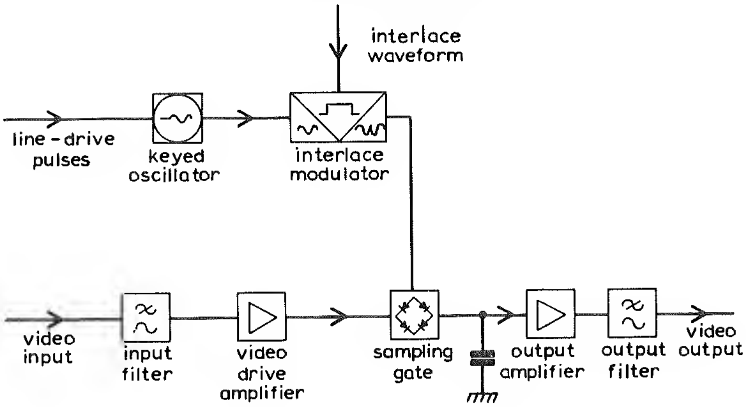


*Fig. 6*
*Equipment used in the tests*

capacitor was connected to the output of the gate. The gate was switched on by sampling pulses of a duration sufficient to allow the capacitor voltage to reach the input voltage, and was then switched off until the next sample was taken. The capacitor held the output voltage constant between the samples. This arrangement of gate and capacitor is termed a 'box-car' circuit.[11] Such a circuit has an amplitude/frequency response which has a 'zero' at the sampling frequency and falls somewhat between d.c. and half the sampling frequency; the response of the output amplifier was adjusted to compensate for this fall.

If it may be assumed that the portrayal of information along the vertical axis of the displayed picture does not substantially influence the visibility of the effects of sampling on the portrayal of information along the horizontal axis, the output of the circuit used in these tests represented a standards converted signal as far as the effects of sampling are concerned. A picture converted to the 405/50 standard from the 625/50 standard should contain all the information along the horizontal axis that can be carried by the 405/50 standard and should therefore correspond to 480 discrete picture points per active line period. This corresponds to a maximum video frequency of 4·62 Mc/s at the 625/50 standard.

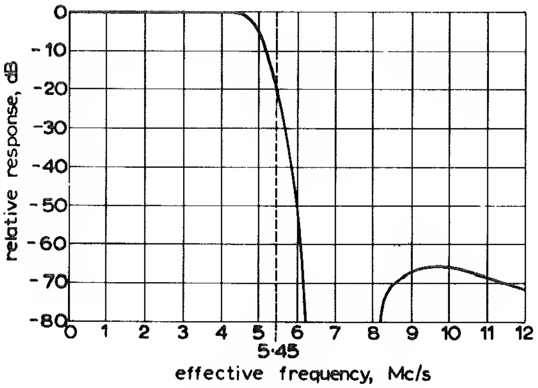


*Fig. 7 - Characteristic of filters used in the tests*

However, the filters[9] that were available for use in these tests had a passband which was limited to 4·5 Mc/s. Their characteristic is shown in Fig. 7. Each consisted of two filter units of the type described in Reference 9, connected in tandem. The use of two units was necessary since the minimum stop-band attenuation of a single unit was less than that required to remove low-frequency image components. The second unit had a cut-off frequency higher than that of the first, so that the first unit determined the passband of the combination. Fig. 3 indicates that the effects of a low sampling frequency are first observed at frequencies near to the limit of the filter pass-band. In order to take account of the limited passband available, the width of the raster of the flying-spot scanner was adjusted slightly so that the highest-frequency bars in a Test Card 'C' slide used in the tests were reproduced at 4·5 Mc/s instead of at 4·62 Mc/s; the width of the displayed picture at the output was also adjusted slightly in order to maintain correct geometry. In this way, the reduced passband involved a reduction in the width of the displayed picture but not the subjective appearance of detail within the available picture area.

This means that when the signal was sampled at a frequency $f_s$, the subjective effect was identical to that which would have been obtained using a video signal, having a spectrum limited to 4·62 Mc/s, sampled at a frequency

$$f_{se} = f_s \cdot \frac{4{\cdot}62}{4{\cdot}5}$$

The sampling frequencies used in the tests were therefore multiplied by 4·62/4·5 and then referred to as 'effective' sampling frequencies ($f_{se}$).

Since the active line duration of the 625/50 standard is 52 $\mu$s, a sampling frequency of $f_{se}$ c/s simulated the effect of (52/10)6 . $f_{se}$ stores in a line-store converter. For instance, sampling at 9·24 Mc/s, as required by the sampling theorem, simulated the effect of 480 stores.

The sampling pulses were derived from an oscillator having an effective frequency which could be continuously varied within the range 4·5 Mc/s to 14 Mc/s. The oscillator was switched off and on by the leading and trailing edges of each line drive pulse, so that oscillations started in the same phase at the beginning of each television line. Sampling was therefore coherent from line to line, as in a line-store converter.

Interlacing of samples was effected by switching between two phase-opposed versions of the oscillator output, using a ring modulator. The switching waveform applied to the modulator consisted of a suitable rectangular wave derived from line and field drive pulses, the form of the wave depending on the type of interlacing required.

When investigating the effect of sampling on pictures having horizontal movement, a 0·5 c/s sine-wave was used to control the line-shift current of the flying-spot scanner. The movement of the image produced in this way extended over a distance corresponding to about 5 picture elements.

## 4. TEST PROCEDURE

The output of the apparatus was displayed on a 21 in (53 cm) high-quality monitor at a peak brightness of 20 ft Lamberts (220 asb) with an ambient illumination of 0·5 ft Lambert* (5 asb). The picture was viewed by a group of six experienced observers positioned at a distance of five times picture height. The observers were asked to comment on the nature of any disturbance produced by sampling, and to assess its visibility according to the following six-point impairment scale:

1. Imperceptible
2. Just perceptible
3. Definitely perceptible but not disturbing
4. Somewhat disturbing
5. Very disturbing
6. Unusable

Three slides, shown in Fig. 8, were used in each test. The pictorial subject shown in Fig. 8(b) contains a large number of well-defined vertical edges, whilst that shown in Fig. 8(c) is mainly made up of gradual changes in brightness. These two slides were, therefore, thought to be representative of a wide range of television subjects.

* The brightneas of a piece of white paper held againat the acreen of the c.r.t., the beam being cut off.

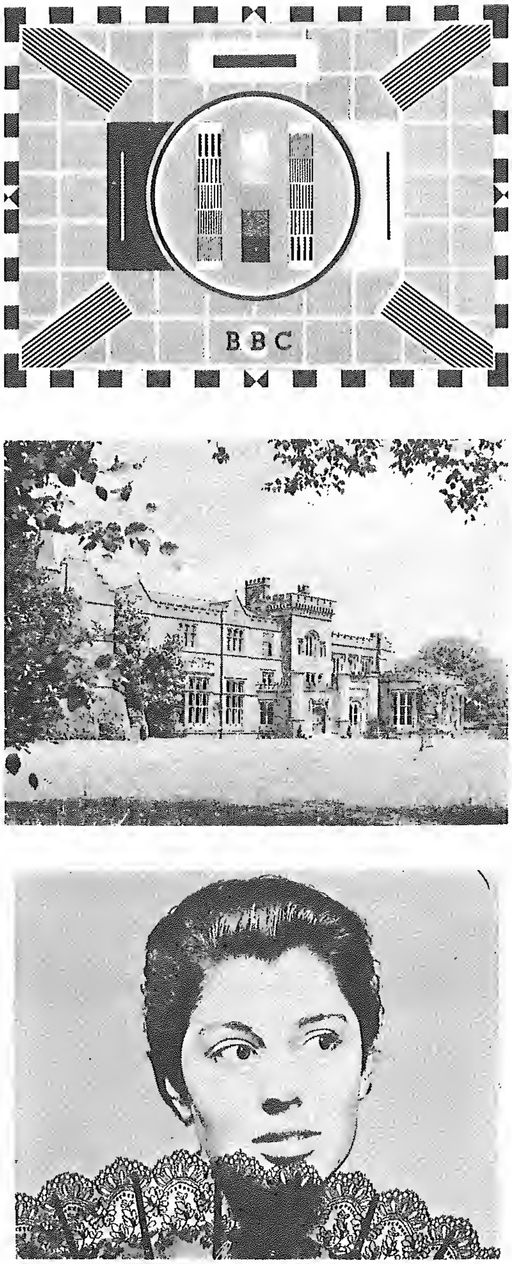


*Fig. 8 - Pictures used in the tests*

The object of the first series of tests was to determine a minimum acceptable sampling frequency. The three pictures were sampled at effective sampling frequencies of 12·3, 9·2, 8·2, 7·2 and 5·65 Mc/s, both when stationary and when moving slowly horizontally. These particular sampling frequencies were chosen solely for instrumental convenience.

The three forms of interlaced sampling illustrated in Fig. 5 were employed in a second series of tests. Each interlacing arrangement was used, with both stationary and moving pictures, at three sampling frequencies. Each test was followed immediately by a similar test without interlacing so that a direct comparison could be made.

## 5. RESULTS

### 5.1. Appearance of Sampled Pictures

No disturbance to the picture was apparent if the sampling frequency was greater than the theoretical minimum frequency determined in the Appendix. However, spurious effects became visible as the sampling frequency was reduced below this value. The deterioration was characterized by errors in the horizontal position of picture detail, caused by the restriction of horizontal brightness changes to discrete positions. The picture was therefore divided into a number of vertical striations, so that vertical edges were displaced, sloping edges appeared 'stepped', and repetitive horizontal detail was obscured by low-frequency patterns.

Although pictorial subjects were, on average, not seriously affected by a low sampling frequency, certain critical pictures such as test cards were considerably degraded. Figs. 9(a) and 9(b) show Test Card 'C' sampled at frequencies of 6·75 Mc/s and 4·5 Mc/s. The residual high-frequency components shown in the finest vertical test-bar patterns of Fig. 9(b) are due to the fact that the voltage on the sampling-gate capacitor followed, to some extent, the input voltage during the time that the gate was open. Some high-frequency video components were thus coupled directly from input to output. This effect was negligible in the most interesting range of effective sampling frequencies, that is from 8 Mc/s to 10 Mc/s.

1. Image component at 2¼ Mc/s interferes with wanted video signal at 4½ Mc/s to produce beat component at 2¼ Mc/s

2. Image component at 3 Mc/s interferes with wanted video signal at 3¾ Mc/s to produce beat component at ¾ Mc/s

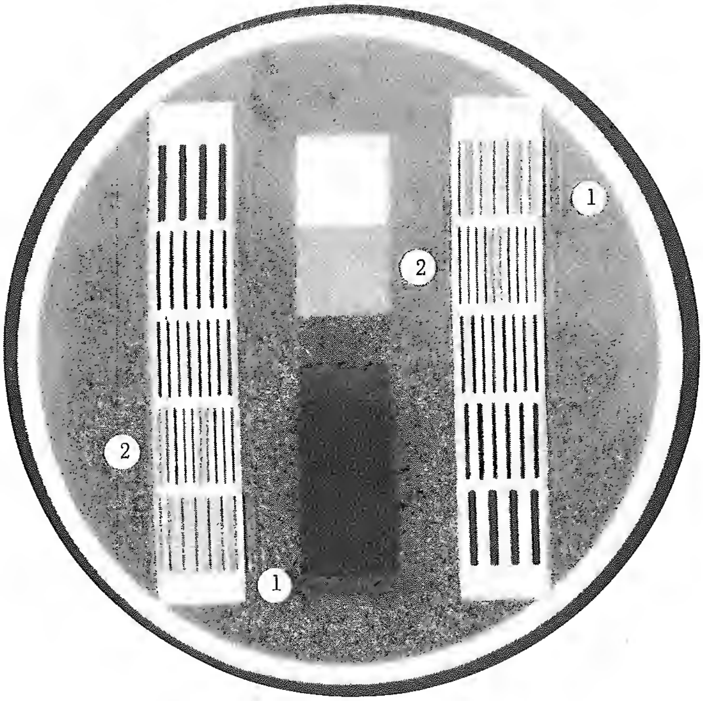


*Fig. 9(a) - A section of Test Card 'C' sampled at 6·75 Mc/s*

1. 4½ Mc/s video signal sampled at positive peaks by 4½ Mc/s sampling signal

2. 4½ Mc/s video signal sampled at negative peaks by 4½ Mc/s sampling signal

3. Beat between 3¾ Mc/s video signal and 4½ Mc/s sampling signal

4. Beat between 3 Mc/s video signal and 4½ Mc/s sampling signal

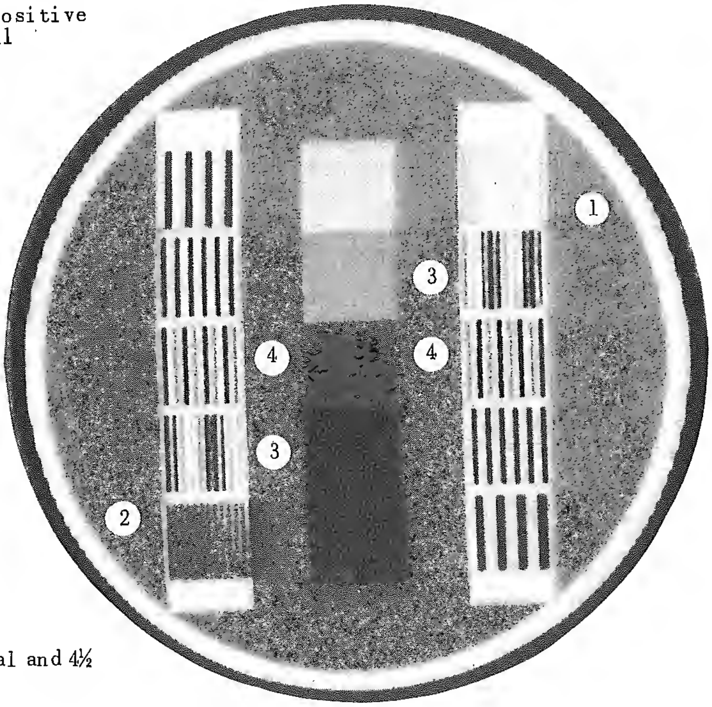


*Fig. 9(b) - A section of Test Card 'C' sampled at 4·5 Mc/s*

The effect of a low sampling frequency was found to be more objectionable with pictures having horizontal movement than with stationary pictures. First, the low-frequency spurious patterns, generated in regions of repetitive fine detail, appeared to move with respect to the moving detail. Secondly, at certain speeds of movement, the rate of progression of vertical edges from one vertical striation to another became comparable with the field frequency. A beat frequency was therefore generated which disturbed the portrayal of motion and produced 'judder'.

Interlacing of samples on successive lines of a field appeared to improve the resolution obtained with low sampling frequencies but introduced a crawling pattern on vertical edges which proved very objectionable, particularly with stationary pictures. This crawling pattern was somewhat similar in appearance to the sub-carrier dot pattern associated with NTSC colour pictures.

Interlacing of samples on successive fields resulted in a marked improvement in the resolution of moving pictures at low sampling frequencies, but the 25 c/s flicker which it introduced at vertical edges was objectionable.

Interlacing samples according to the 'three lines-to-two lines' system produced a pattern which, though it did not flicker or crawl, was sufficiently coarse to mask any improvement in resolution.

### 5.2. Subjective Assessment

Figs. 10(a) and 10(b) give the results of the first series of tests. Each curve shows the mean subjective grading (see impairment scale in Section 4) plotted against effective sampling frequency. A scale of $f_{se}/F_{se}$ is also included, which relates the sampling frequencies shown in the diagrams to the theoretical minimum frequency derived in the Appendix. Fig. 10(a) shows the observers' assessment using each of the three slides; Fig. 10(b) gives a comparison between stationary and moving subjects, based on average assessments obtained using all three slides.

Since the tests on the three systems of interlaced sampling would have been lengthy if all combinations of sampling frequency and subject had been investigated, it was decided to reduce the number of sampling frequencies. The interlace tests were therefore carried out at effective sampling frequencies of 5·65 Mc/s, 8·2 Mc/s, and 12·3 Mc/s only. The results of these tests are summarized in Table 1. This table shows average assessments based on both interlaced and non-interlaced sampling of all three slides, when stationary and when moving.

*TABLE 1*

*Results of Tests Involving Interlaced Sampling*

| $f_{se}$ | AVERAGE ASSESSMENT | | |
|---|---|---|---|
| | 5·65 Mc/s | 8·2 Mc/s | 12·3 Mc/s |
| No interlace | 3·8 | 2·3 | 1 |
| 1 : 1 Line interlace | 4·2 | 2·8 | 1 |
| 1 : 1 Field interlace | 3·2 | 2·2 | 1 |
| 3 : 2 Line interlace | 3·6 | 2·5 | 1 |

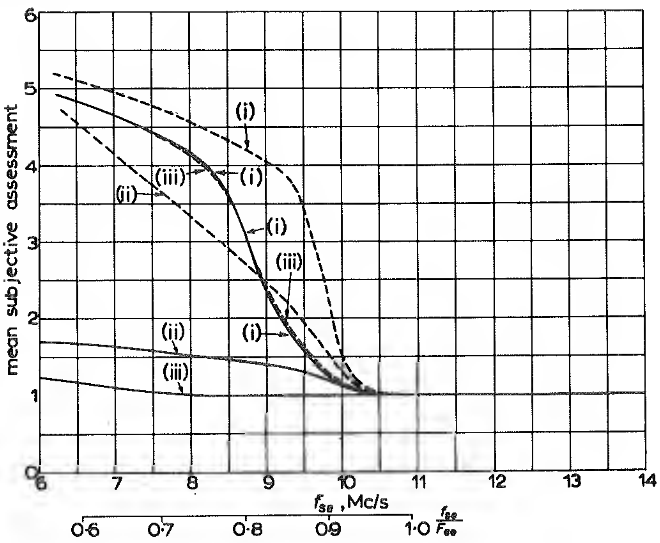


*Fig. 10(a)*
*Results of non-interlaced sampling tests - effect of picture content*

(i) Test Card 'C'
(ii) Building
(iii) Portrait

——— Stationary
- - - - Moving

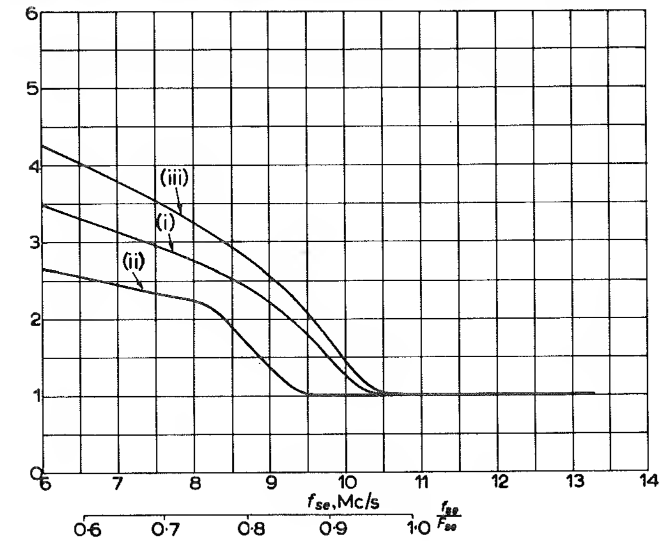


*Fig. 10(b)*
*Results of non-interlaced sampling tests - effect of horizontal movement*

(i) Mean of all tests
(ii) Mean of tests on stationary subjects
(iii) Mean of tests on moving subjects

## 5.3. Discussion of Results

The subjective tests have shown that if spurious effects due to sampling are to be invisible, the effective sampling frequency should be no less than 10·5 Mc/s. This is twice the frequency at which each of the filters attenuates by 12 dB. (This result should be compared with the attenuation figure of 20 dB derived from the theoretical analysis.) The implication of the experimental result is that a line-store converter operating between the 625/50 and 405/50 standards, and using low-pass filters of the type described above, should contain at least 546 stores.

The theoretical analysis led to a minimum sampling frequency of 10·9 Mc/s, corresponding to 567 stores. The difference in the two results arises because the theoretical analysis is based on the visibility of an interference pattern which is present over the whole picture and unrelated to picture detail. Such a pattern is considered to be more readily perceived than the effects resulting from imperfect sampling, and it is therefore to be expected that the theoretical analysis would yield a somewhat higher minimum sampling frequency than that which is actually necessary.

Only field-interlaced sampling was considered preferable to non-interlaced sampling on pictures of all types. However, it gave a negligibly small improvement except for sampling frequencies so low that the picture was seriously degraded either with or without it. Where a picture is required in which sampling effects are imperceptible, field-interlaced sampling would not permit the sampling frequency to be lowered by more than about 5%.

## 6. CONCLUSIONS

The sampling theorem states that all of the information contained within a signal occupying a bandwidth of $w$ c/s may be carried by a train of amplitude-modulated samples provided that the rate of sampling is not less than 2 $w$ per second. This theorem should be modified when practical low-pass filters are used to limit the signal spectrum. The subjective tests described in this report have indicated that, when certain high-grade filters of identical design are used before and after sampling, the minimum sampling frequency should be twice the frequency at which each filter attenuates by 12 dB. Thus a line-store converter operating between the 625/50 and 405/50 standards, and using filters of this type, should contain at least 546 stores. A theoretical analysis, based on conditions which are thought to be more stringent than those which apply in such a converter, leads to a somewhat higher minimum sampling frequency.

Reduction of the sampling frequency, or number of stores, below the minimum defined above, produces a deterioration in picture quality. The deterioration is in general more severe for moving pictures than for stationary ones; it is most severe for moving test cards and other moving pictures which have clearly defined vertical edges.

The three simple systems of interlaced sampling which were tried did not offer any significant advantage; whilst these systems gave an apparent improvement of resolution at low sampling frequencies, they introduced other effects which counterbalanced this improvement. Field interlacing of the samples was the only interlacing system to show an overall advantage. However, this advantage was slight and it is likely that the instrumental complication involved in incorporating field-interlaced sampling in a line-store converter would more than offset the possible reduction in the number of stores.

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## *APPENDIX*

### *Derivation of a Theoretical Minimum Sampling Frequency*

The effect of imperfect sampling is to introduce image components into the video band. Fig. 11 shows how these image components arise for three different sampling frequencies, $f_s$. After sampling, any signal at frequency $f$, within the video spectrum, has a corresponding image signal at frequency, $|f_s - f|$, associated with it. If this image signal falls within the passband of the output filter, an image component appears in the output signal. Such components can exist only in the cross-hatched portions of the 'filtered-output' spectra shown in Fig. 11.

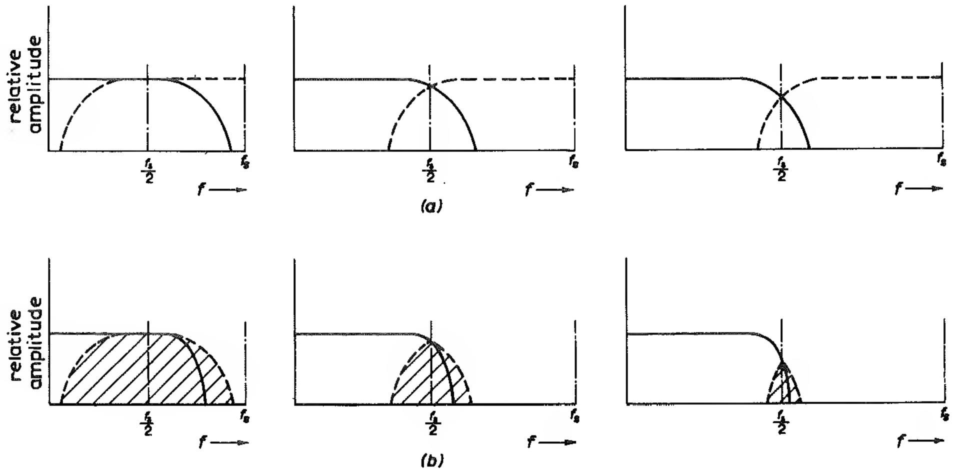


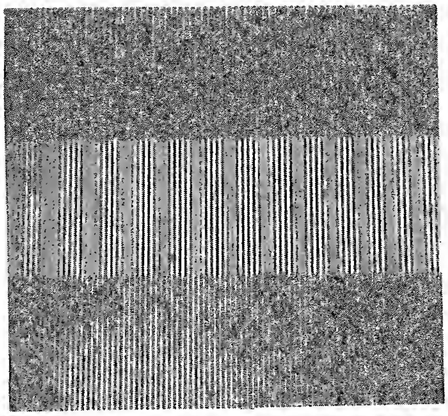

*Fig. 11 - The production of image components*

(a) Spectrum of sampled signal
(b) Filtered spectrum of output signal

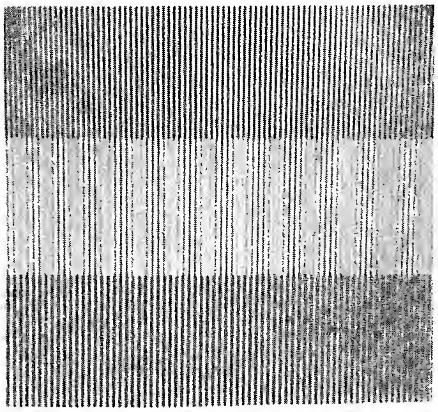
——— video spectrum
- - - - - image spectrum
////. image apectrum present in output

When a video-frequency component and its image are present together at the output of a sampling device, it might be expected that the interference pattern produced by their addition would be no more visible than the image component viewed separately. However, the cathode-ray tube (c.r.t.), which displays the output picture from a line-store converter, has a characteristic which may be expressed as $b = v^{2 \cdot 5}$ where $b$ is the brightness of the display, and $v$ is the signal voltage relative to the tube cut-off voltage. This non-linearity produces intermodulation of the signals simultaneously applied to the tube. Therefore, when a video-frequency component and its image are applied together to the tube, a beat-frequency brightness component is produced in addition to the interference pattern produced by the simultaneous presence of two fine patterns (the wanted pattern and its image) at the screen of the c.r.t.

This is illustrated in Fig. 12(a) which shows two grating patterns of slightly different pitch, simultaneously projected on to a screen from separate optical projectors. A substantially linear photographic process has been used and although no modulation has taken place, there is the impression of a beat-frequency component. This is not due to a change in mean brightness but to a change in the



(a) Linear reproduction



(b) Non-linear reproduction

*Fig. 12 - Addition of two grating patterns*

pattern structure, occurring at the difference frequency. This interference pattern is no more visible than either of its two components viewed separately. The fact that no beat-frequency brightness component is present may be seen by holding Fig. 12(a) at such a distance that the fine patterns cannot be discerned. Little trace of the difference frequency remains. Fig. 12(b) shows the same addition of grating patterns reproduced by a non-linear photographic process. In this case the brightness pattern at difference frequency is readily visible when the figure is viewed at a considerably greater distance.

When an upper video-frequency component and its image are simultaneously present, the input to the c.r.t. may be expressed in the form:

$$1 + a \cos \omega_1 t + b \cos \omega_2 t = 1 + f(t)$$

where $a \cos \omega_1 t$ is the video-frequency component,

and $b \cos \omega_2 t$ is the image component.

The displayed brightness will then be

$$b(t) = \{1 + f(t)\}^{2\cdot 5}$$

which may be expanded by the Binomial Theorem as:

$$b(t) = 1 + 2{\cdot}5\ f(t) + \frac{(2{\cdot}5)(1{\cdot}5)}{(1)(2)} [f(t)]^2 + \frac{(2{\cdot}5)(1{\cdot}5)(0{\cdot}5)}{(1)(2)(3)} [f(t)]^3 + \ldots\ldots$$

Difference-frequency components of the form $\cos (\omega_1 - \omega_2)t$ result only from terms involving $[f(t)]^2$, $[f(t)]^4$, etc., and of these only the $[f(t)]^2$ term is of significant magnitude. This term is:

$$15/8\ (a \cos \omega_1 t + b \cos \omega_2 t)^2$$

which yields the difference term:

$$15ab/8 \cos (\omega_1 - \omega_2)t$$

(Sum terms and harmonics of the difference-frequency signal are also produced, but their visibility is less.)

These difference-frequency components may be observed in Fig. 9(a), associated particularly with the vertical test-bar patterns within the circle. They are obscured in Fig. 9(b) because, in this case, the sampling frequency itself falls within the passband of the output filter.

From the above arguments, it follows that a theoretical determination of a minimum sampling frequency must take account of two requirements. The pattern produced by the addition of image components to the wanted video signal must be invisible, and the beat-frequency component due to inter-modulation of the wanted and unwanted components by the non-linearity of the display tube must also be invisible. These two effects have been considered separately, using the results of a series of subjective tests made to establish the visibility of the interference pattern produced when a television transmission suffers co-channel interference from a c.w. signal.

Consider first the effect of modulation due to the non-linearity of the display tube. At the highest sampling frequency at which spurious effects are visible, the beat-frequency components produced by modulation are seen as low-frequency interference in regions of fine detail.

Curve (a) of Fig. 13 is an enlarged section of part of the (input) filter characteristic shown in Fig. 7. It can represent, therefore, part of the video

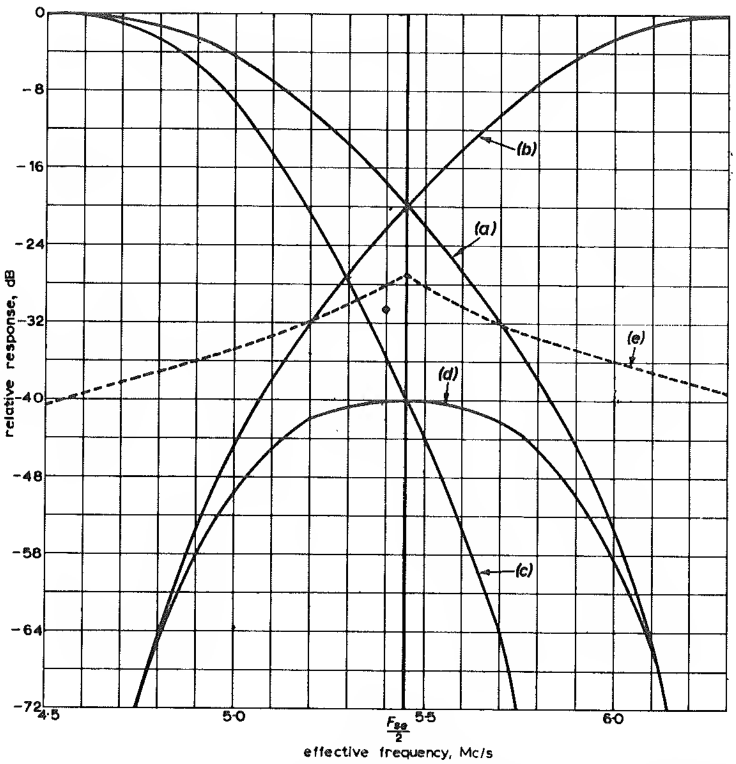



*Fig. 13 - Spectra of wanted signal and high-frequency interference components*

(a) Part of filter characteristic
(b) Image spectrum introduced by sampling at $F_{se}$
(c) Video spectrum of output signal
(d) Spectrum of image signal in the output
(e) Estimated curve showing the level of an interfering c.w. signal corresponding to the threshold of visibility

spectrum applied to the sampling gate. Curve (b) of Fig. 13 shows the image spectrum which results from sampling at a theoretical effective frequency, $F_{se}$, of 10·9 Mc/s. The spectra of the wanted and unwanted products of sampling are limited by the filter connected at the output of the gate. If this filter is identical to the input filter, the spectrum of the wanted output signal will be as shown in curve (c) and the unwanted spectrum as shown by curve (d).

The magnitude of the beat-frequency components resulting from inter-modulation by the display tube will be $15ab/8$ where '$a$' is the magnitude, taken from curve (c), of a single-frequency wanted component and '$b$' is the magnitude, taken from curve (d), of the associated image component.

The spectrum of the beat-frequency components produced in this way, when the effective sampling frequency is 10·9 Mc/s, is plotted in Fig. 14.

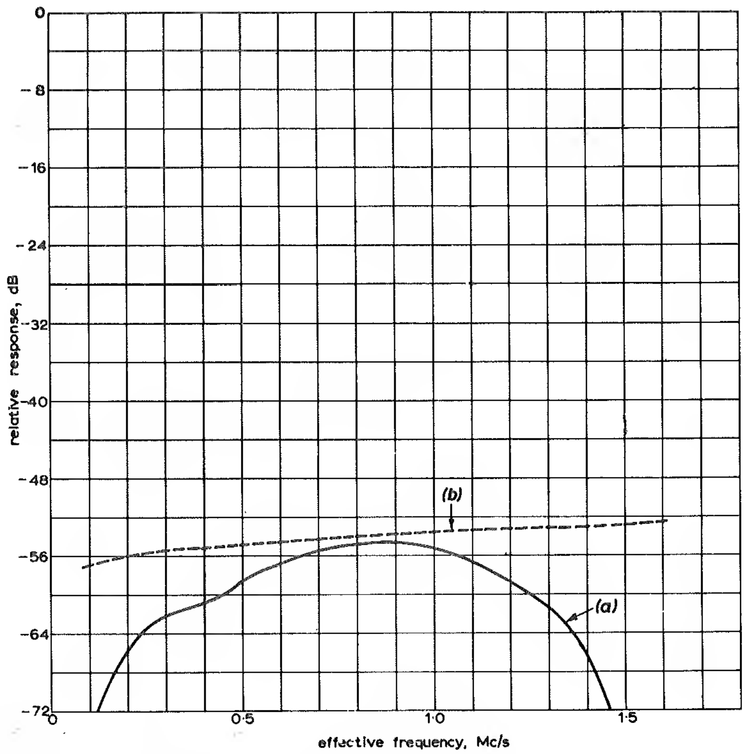



*Fig. 14 - Spectrum of low-frequency interference components produced by inter-modulation at the c.r.t.*

(a) Interference components

(b) Estimated curve showing the level of an interfering c.w. signal corresponding to the threshold of visibility

Investigations into the subjective effect of co-channel interference[12] have yielded a curve* showing the level at which a single-frequency interfering signal injected into a television receiver becomes visible. This curve has been modified by a factor of 6 dB, since it relates to signals injected at radio frequency, and by a further 3 dB, since the magnitude of the interference was measured relative to a composite video waveform. The relevant parts of the modified curve are plotted as dotted lines in Figs. 13 and 14.

Figs. 13 and 14 have been drawn with $F_{se}$ chosen so that the low-frequency interference curve is entirely below the curve corresponding to threshold visibility. For values of $F_{se}$ lower than 10·9 Mc/s the magnitudes of beat-frequency components exceed the limits imposed by the threshold curve and can therefore be seen. Therefore, in order that components due to modulation shall not be visible, the sampling frequency should not be less than 10·9 Mc/s.

Consider now the effect of the pattern produced by the addition of unwanted image components to the video signal. As previously stated, this pattern will be invisible if the image components are themselves invisible. Curve (d) of Fig. 13 shows that if the sampling frequency is 10·9 Mc/s, the image spectrum at the output of the sampling device is restricted to a band of high frequencies (4·75 to 6·15 Mc/s), and is attenuated, with reference to the main signal by not less than 40 dB. This spectrum is entirely below the corresponding threshold curve, in the conditions depicted in Fig. 13, and the high-frequency image components are thus invisible.

This analysis suggests, therefore, that where filters of the above design and cut-off frequency are used, the sampling frequency should be not less than 10·9 Mc/s. This frequency is twice the frequency at which the filters attenuate by 20 dB.

The above arguments assume that the results of co-channel interference tests, which relate to a single-frequency interference pattern present over the whole picture and having no coherence with picture detail, may be applied to localized sampling effects involving interference occupying a band of frequencies. It is thought that an interfering signal over the whole picture would be the more readily perceived effect. If this is so, then use of the results of co-channel interference tests leads to a minimum sampling frequency somewhat higher than that which is actually necessary.

The shape of the curve shown in Fig. 14 is very dependent on the shape of the filter response near cut off, curve (a) of Fig. 13. The figure of 20 dB obtained in this analysis should not necessarily be applied to other designs of low-pass filters, but the graphs in Figs. 13 and 14 should be re-plotted for each new case.

Figs. 13 and 14 indicate that image components are invisible over the whole video band only if the filter response, after falling to -56 dB, remains below this figure. Furthermore, the rate of increase of attenuation at frequencies above $F_{se}/2$ must be sufficiently rapid to prevent any image components rising above the threshold curve shown in Fig. 13.

*Curve (b), Fig. 3 of Reference 12.

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